

# MODEL-BASED RESPIRATORY MOTION CORRECTION USING 3-D ECHOCARDIOGRAPHY

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## ABSTRACT

In this paper we investigate the use of 3-D echocardiography (echo) data for respiratory motion correction of MRI-derived roadmaps in image-guided interventions. By a combination of system calibration and tracking the MRI and echo coordinate systems are aligned. 3-D echo images at different respiratory positions are registered to an end-exhale 3-D echo image using a registration algorithm that uses a similarity measure based on local orientation and phase differences. We first assess the use of the echo-echo registration alone to perform motion-correction in the MRI coordinate system. Next, we investigate combining the echo-echo similarity measure with a MRI-derived motion model. Using experiments with cardiac MRI and 3-D echo data acquired from 2 volunteers, we demonstrate that significantly faster and more robust performance can be obtained using the motion model.

**Index Terms**— Echocardiography, respiratory motion, modelling, MRI

## 1. INTRODUCTION

The excellent soft tissue contrast of magnetic resonance imaging (MRI) data makes it useful for guiding a range of image-guided interventions. For example, in [1] an MRI-derived roadmap was overlaid onto real-time X-ray images for XMR (X-ray/MRI) guided cardiac catheterisation procedures. In the chest and abdomen, the accuracy of such systems is significantly reduced by respiratory motion. Most solutions to overcome this difficulty have involved a motion model and a simple surrogate of respiratory phase, such as diaphragm motion [2][3]. These approaches require there to be a known relationship between the surrogate measurement and the position of the target organ. A more direct approach is to combine the use of a motion model with intraprocedure imaging of the target organ [4]. This paper aims to extend this direct approach: we make use of the recent rapid advances in 3-D echo technology which now enable the near real-time acquisition of cardiac volumes, along with developments in echo-echo similarity measures [5]. Our method uses a previously constructed MRI-derived motion model [2] to constrain a registration between 3-D echo images in order to compute estimates of respiratory motion. We demonstrate our technique using cardiac MRI and 3-D echo data. The method has potential application in a range of image-guided interventions in the chest and abdomen.

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## 2. METHOD AND MATERIALS

### 2.1. Materials

All experiments were carried out in the XMR suite at Guy's Hospital, London, which features a 1.5 Tesla cylindrical bore Philips Achieva MRI scanner. Subjects can be moved out of the MRI scanner on a sliding bed, which has infrared light emitting diodes (LEDs) attached to enable it to be optically tracked. A combination of system calibration and tracking was used to calculate the MRI image to physical space transformation with an accuracy of 2mm [1]. The motion of the bed was tracked using an Optotrak 3020 optical tracking system (Northern Digital Inc).

For 3-D echo acquisition we used an iE33 3-D real-time echocardiography system with a X3-I 3 to 1 MHz broadband matrix array transducer (Philips Medical Systems). Infrared LEDs were attached to the echo probe to enable it to be tracked. The probe was calibrated using the method described in [6].

### 2.2. Data Acquisition

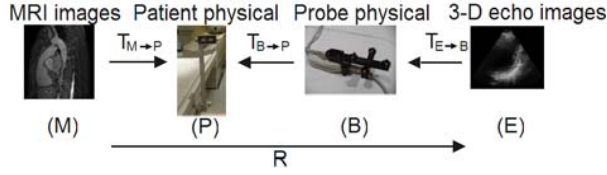
A number of MRI scans were acquired to perform the experiments described in this paper. Each scan covered the four chambers and major vessels of the heart. Two different MRI scans were acquired to form the motion model. First, a high resolution volume was acquired (3-D balanced TFE scan, gated at exhale and cardiac triggered and gated at late diastole, typical reconstructed voxel size  $1.37 \times 1.37 \times 1.37\text{mm}^3$ , 140 sagittal slices,  $160 \times 119$  matrix, scan time approximately 5 minutes). This is also used to form the MRI-derived roadmap. Next, a dynamic near real-time scan is used to determine the respiratory motion (multislice balanced TFE, cardiac triggered and gated at late diastole, typical reconstructed voxel size  $1.1 \times 1.1 \times 8.0\text{mm}^3$ , 2 sagittal slices separated to cover the area of interest,  $252 \times 183$  matrix, 120 dynamics, scan time approximately 2 minutes). During this scan subjects were instructed to perform normal, fast and then deep breathing to ensure that the model was applicable in a range of different breathing patterns.

For validation purposes (see Section 2.5), we also acquired a number of breath-hold MRI images (3-D balanced TFE scan, cardiac triggered and gated at late diastole, typical reconstructed voxel size  $1.37 \times 1.37 \times 6.0\text{mm}^3$ , 25 sagittal slices,  $160 \times 120$  matrix, scan time approximately 25 seconds). These images were acquired at normal inhale.

For each experiment, a pair of 3-D echo images was acquired: one at exhale and one at normal inhale. The volunteers were instructed to hold their breath at the same position that the breath-hold MRI scans were acquired at. The 3-D echo images were acquired by an experienced ultrasonographer from two standard views: a modi-

fied parasternal long-axis view covering the left atrium, left ventricle, and left ventricular in- and out-flow tract; and a modified subcostal four chamber view. The 3-D echo images were cardiac gated at late diastole by synchronising image acquisition with the signal from the electrocardiogram.

Figure 1 illustrates the different coordinate systems involved in the experiments. The overall MRI to echo registration,  $R$ , is comprised of three transformations.  $T_{M \rightarrow P}$  is the transformation resulting from tracking of the patient bed and calibration of the XMR image guidance system.  $T_{B \rightarrow P}$  is found by tracking the echo probe and the patient bed.  $T_{E \rightarrow B}$  is the result of calibrating the echo probe.



**Fig. 1.** Computing the MRI-echo registration,  $R$ .

### 2.3. The MRI-Derived Motion Model

The motion model we employ is based on that described in [2]. Briefly, the model is constructed from a short dynamic MRI scan and a high resolution exhale MRI volume. To form the model, every dynamic acquisition (each of which is acquired at an arbitrary respiratory position) is automatically registered to the high resolution exhale MRI volume using an affine intensity-based registration algorithm. The normalised mutual information similarity measure was computed over a manually defined elliptical region of interest centred on the four chambers of the heart. The twelve affine motion parameters resulting from the registrations are modelled as polynomial functions of the MRI navigator value. The model is a slight simplification of that described in [2], in that the inspiration and expiration phases are not modelled separately, and only first order polynomial functions (i.e. linear fit) are used.

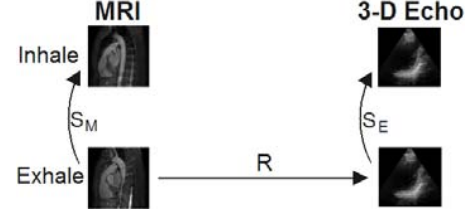
We denote a motion model by  $M$ . Applying the motion model using a navigator value  $V$  to produce an affine transformation is denoted by  $M(V)$ .

### 2.4. 3-D Echo-Based Motion Correction

We test two alternative techniques for 3-D echo-based respiratory motion correction. Both use the results of an echo-echo similarity measure based on local orientation and phase differences [5] between exhale and inhale 3-D echo images. Prior to registration, each inhale 3-D echo image was transformed to the coordinate system of the exhale 3-D echo image using the probe tracking and calibration transformations. Motion-correction transformations were computed in exhale 3-D echo coordinates, and used to find the corresponding transformation in MRI coordinates,  $S_M$ , using the following relationship,

$$S_M = R S_E R^{-1}. \quad (1)$$

where  $R = T_{M \rightarrow P}^{-1} T_{B \rightarrow P} T_{E \rightarrow B}$ , as illustrated in Figure 1, and  $S_E$  is the motion-correction estimate in exhale 3-D echo coordinates. Figure 2 illustrates how the echo-echo registration can be used for motion correction in MRI coordinates.



**Fig. 2.** Computing the MRI motion-correction transformation. Breath-hold 3-D echo images are acquired at exhale and inhale. The echo-echo transformation,  $S_E$ , together with the known MRI-echo registration at exhale,  $R$ , are used to compute the MRI-MRI transformation,  $S_M$ . These are used to warp the exhale MRI image to inhale. For validation purposes, the warped MRI image is compared with a breath-hold MRI image acquired at the same inhale respiratory position.

The first motion-correction technique uses only the echo-echo registration result to motion-correct the MRI-derived roadmap. The motion-correction transformation,  $S_E$  is estimated by varying the motion parameters,  $\phi$ , to optimise the similarity measure. We tested only rigid registration for this technique, so  $\phi = (T_x, T_y, T_z, \theta_x, \theta_y, \theta_z)$ . The 3-D echo motion-correction transformation,  $S_E$ , is estimated as

$$S_E = A(\tilde{\phi}) \quad (2)$$

where

$$\tilde{\phi} = \underset{\phi}{\operatorname{argmax}} \operatorname{Sim}(A(\phi) \cdot \text{Echo}_{\text{exhale}}, \text{Echo}_{\text{inhale}}) \quad (3)$$

In (2) and (3),  $A(\tilde{\phi})$  is the transformation produced from the motion parameter estimate,  $\tilde{\phi}$ , and  $\operatorname{Sim}$  is the phase-based similarity measure [5].

The second technique combines the echo-echo similarity measure with a MRI-derived model of respiratory motion. This technique computes the similarity measure on the 3-D echo images but only allows transformations permitted by the MRI-derived motion model. When optimising the similarity measure it allows variation in only a single term, the MRI navigator value,  $V$ , which is used as the input to the motion model,

$$S_E = M(\tilde{V}) \quad (4)$$

where

$$\tilde{V} = \underset{V}{\operatorname{argmax}} \operatorname{Sim}(M(V) \cdot \text{Echo}_{\text{exhale}}, \text{Echo}_{\text{inhale}}) \quad (5)$$

### 2.5. Validation

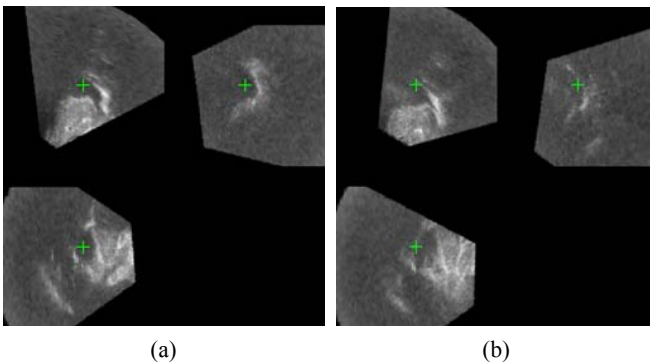
We validated the proposed motion-correction techniques using MRI data acquired from 2 volunteers. First, to validate the volunteers' ability to hold their breath repeatedly at the same respiratory position, the normal inhale breath-hold MRI scan was acquired 5 times. Seven anatomical landmarks located in a range of positions within the four chambers of the heart were manually localised in each image. Mean locations were computed for each landmark, and a root mean square (RMS) error away from these mean locations was computed over all 5 images.

For each volunteer, a number of 3-D echo images were acquired at both the exhale and inhale respiratory positions. The motion correction transformations were computed using the rigid echo-echo registration result and also the affine motion-model based technique. The resulting transformations were used to motion-correct the anatomical landmarks from the exhale MRI image, using the relationship given in (1). The motion-corrected landmarks were compared with the landmarks localised in the inhale breath-hold MRI images. For each volunteer we performed 2 experiments, using different pairs of exhale/inhale 3-D echo images, each pair acquired from a different view.

### 3. RESULTS

The results for the breath-hold repeatability tests demonstrated that both volunteers were able to hold their breath in the same inhale position with a repeatability error of approximately 1mm. The figure for volunteer A was 1.1mm and that for volunteer B was 0.6mm.

Sample 3-D echo images are shown in Figure 3. Both exhale and inhale images show the cursor positioned inside the right atrium. The inferior vena cava can be seen to the bottom right of the cursor in the top left (sagittal) slices.

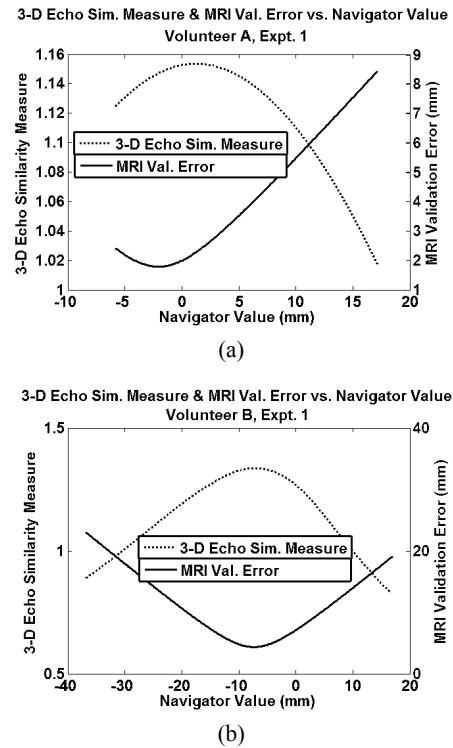


**Fig. 3.** Three orthogonal slices through sample 3-D echo images. (a) volunteer A, expt. 1, exhale image; (b) volunteer A, expt. 1, inhale image

Table 1 shows the motion-correction results for the two different approaches: rigid echo-echo registration and affine model-based registration.

For the 3-D echo affine model based technique, Figure 4 shows the variation of the 3-D echo similarity measure and the landmark based MRI validation error with navigator value for two sample experiments. In Figure 4(a) the peak of the 3-D echo similarity measure corresponds to a MRI validation measure of 2.3, and in Figure 4(b) the 3-D echo peak corresponds to a MRI validation value of 4.3 (as indicated in Table 1).

As an illustration of the predictive accuracy of the 3-D echo affine model based technique, Figure 5 compares breath-hold inhale MRI images with the high resolution exhale MRI image warped to inhale using transformations predicted by the model-based technique.



**Fig. 4.** The variation of the 3-D echo similarity measure and the landmark based MRI validation error with navigator value: (a) volunteer A, expt 1; (b) volunteer B, expt 1.

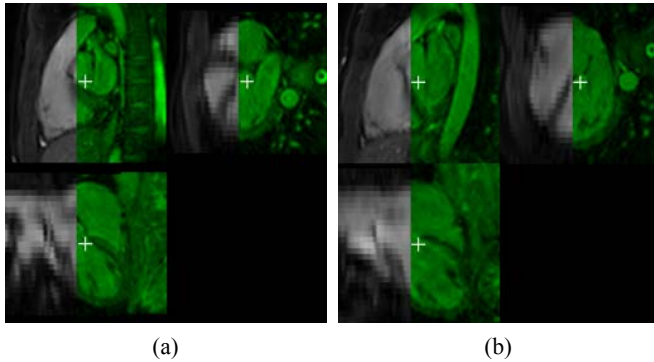
### 4. DISCUSSION AND CONCLUSIONS

The aim of this paper was to demonstrate the feasibility of using 3-D echo data for respiratory motion correction in image-guided interventions. We have shown that impressive results can be obtained, but in the process highlighted a number of potential difficulties. We found that using echo-echo registration alone was not a robust approach. The main reason for this was the quality of the 3-D echo images. Although the images were acquired by an experienced ultrasonographer, routine echocardiography requires repositioning of the subject during the echo study. However, this was not possible for our application as this would invalidate the image to physical registration required by the image-guidance software. Therefore the images were of a lower quality than would normally be expected. Nevertheless, we have shown that combining the echo-echo similarity measure with a MRI-derived motion model enables this difficulty to be overcome. In three of the four experiments the MRI validation error was below 5mm. The poor performance in the fourth case (volunteer B, experiment 2) was not entirely clear, but could have been due to bulk motion of the volunteer, variation in breath-hold position, or deformation due to probe pressure. Also, it is possible that using an increased transducer frequency probe would result in better quality images that might improve the results of both motion-correction techniques we proposed.

As well as providing more robust performance, the proposed model based approach is much faster than the echo-echo registration based approach. In our experiments, the model based approach

Subject	Expt.	Echo View	RMS Errors (mm)		
			Before motion correction	After rigid echo-only motion-correction	After affine model-based echo motion correction
Vol. A	1	Subcostal	9.2	23.3	2.3
	2	Parasternal		4.1	2.4
Vol. B	1	Subcostal	17.6	3.7	4.3
	2	Parasternal		14.3	9.8

**Table 1.** Motion-correction results for the echo-echo rigid registration and the affine motion-model based techniques.



**Fig. 5.** Comparing breath-hold inhale MRI images (light) with the high resolution exhale MRI image warped to inhale using the transformations predicted by the affine model-based motion correction technique (dark) - 3 orthogonal slices: (a) volunteer A, expt. 1; (b) volunteer B, expt. 1

was faster by a factor of four. In addition, because finding the peak of the similarity measure involves varying a single parameter, there is great potential for further speed improvements by using parallel computation of the similarity measure values. Although our current implementation does not work in real-time, we believe that the benefits of parallelism together with code optimisation could make this a real possibility.

We compared only a rigid echo-echo registration based approach with an affine model based approach. We did not include results for affine echo-echo registration. The reason for this was that affine registration using the phase-based similarity measure is known not to be robust [5]. Our own experiments confirmed this. Nevertheless, motion of the heart is better approximated by affine models than by rigid body motion.

The main novelty of this work lies in the combination of a motion model and 3-D echo images to correct for respiratory motion. Our approach makes use of the substantial amount of intraprocedure information that can be acquired of a target organ, in near real time, using modern 3-D echo technology. This has been combined with state-of-the-art image registration technology to produce a novel approach for motion correction. We have demonstrated that this approach is feasible and offers a very promising way forward to correct for respiratory motion in image-guided interventions. Future work will concentrate on incorporating real-time 4-D output of cardiac echo volumes. This will enable the methodology to be tested for free breathing, as opposed to breath holds, which is a more clinically realistic scenario. It should also enable more extensive validation to be

carried out, i.e. the calculation of registration errors throughout the breathing cycle. We also aim to refine the current model-based approach to allow limited deviation from the transformations predicted by the motion model. This new technique will have the potential to make more accurate motion predictions in the presence of variations in the breathing cycle. Our aim is to use and validate this new technique on data acquired during XMR-guided cardiac catheterisations.

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